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Pratt & Whitney Aircraft DIVISION OF UNITED AIRCRAFT CORPORATION

EAST HARTFORD 8, CONNECTICUT

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# First Quarterly Report on Design and Development of Hydrogen-Oxygen Fuel Cell Powerplant

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Written by

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# FOREWORD

This quarterly progress report was prepared by the Pratt & Whitney Aircraft Division of United Aircraft Corporation, East Hartford, Connecticut, in compliance with Contract NAS3-1724. It covers the technical accomplishment on design and development of a hydrogen-oxygen fuel cell powerplant for the three month period from July 1 through September 30, 1961.

## ABSTRACT

The design of the specific 250 watt experimental fuel cell powerplant system required by Task 1 of Contract NAS3-1724 has been completed and detailed drawings have been released for fabrication. The items designed include the fuel cell module assembly, the hydrogen circulation loop pump and heat exchangers, the pressure regulators, hydrogen circulation controls, and electrical components. Fabrication of the hydrogen circulation pump is complete and construction of the other powerplant components has been started. While components of the experimental powerplant were not available for test during this first report period, a total of 1456.5 hours of test time was completed on "breadboard" components (available hardware of an earlier design). These tests will provide design data and systems experience early in the program and facilitate the later testing of an experimental powerplant. The breadboard components tested included single cells, multi-cells, pressure regulators, and a hydrogen circulation loop. Adequate solutions were found for the design problems encountered. None of the testing to date has altered our expectation of demonstrating the feasibility of the hydrogen-oxygen fuel cell powerplant for space applications. Progress is in accordance with the planned program for this period. During the next quarter, it is anticipated that the experimental components will be fabricated, that test evaluation of these experimental components will be started, and that a complete breadboard powerplant will be tested.

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# I. INTRODUCTION

## Objective

The objective of this program is to design, fabricate and conduct development testing of an experimental fuel cell powerplant system to establish the feasibility of a fuel cell power supply for manned space vehicle applications. Upon completion of the development phase, the design of a prototype fuel cell power supply for a manned space vehicle will be furnished.

## Fuel Cell Background

Pratt & Whitney Aircraft Division has undertaken an extensive program of fuel cell research and development as a logical extension of a long and varied background in the development of advanced powerplants. In support of this program, exclusive rights to the Bacon fuel cell and all associate technology were acquired in 1959. This cell has been under development since the early 1930's by Francis T. Bacon in Cambridge, England and has been successfully demonstrated in several multicell units.

The Bacon type fuel cell has several basic advantages over other electric powerplants for space applications. The cell converts chemical energy to electrical energy statically at very high efficiency. It operates at sufficiently high temperatures to allow operation at high current densities and to facilitate rejection of waste heat. The product of the conversion process is potable water which is available for use by the crew or for auxiliary equipment. Finally, the dual porosity electrode structure provides a positive separation of liquid and gas phases for operation in a variable gravity environment.

Since 1959, an extensive research and development program has been underway at Pratt & Whitney Aircraft Division, with contributions from several associated university and industrial research laboratories, for the improvement of performance, reproducibility, and reliability of the basic design. Substantial progress has been achieved in all areas. A cell which operates at low pressure (one to three atmospheres instead of twenty to forty) has been developed. Cell performance has been continuously improved as a result of refined electrode fabrication and cell operating techniques. Multicell assemblies of these low pressure units have been demonstrated, one at NASA, Langley Field. Substantial progress has been made with system analysis, fuel cell auxiliary components and controls. A powerplant system has been designed with company funds so that the demonstration of the feasibility of a complete powerplant system appeared to be a practical and desirable next step.

## Scope of Present Program

The program to meet the above stated objective consists of the following specific tasks:

Task 1 - Design, fabricate, and test an experimental low pressure fuel cell powerplant system, incorporating a present state-of-the-art hydrogen-oxygen fuel cell, with the objective of providing a minimum power of 250 watts at a voltage of 12 ± 1 volts and an operating efficiency of not less than 50 per cent at the maximum load conditions.

The test program will include:

a) approximately 3,500 hours of single or multi-fuel cell testing,
b) approximately 1,000 hours of component testing, of such components as controls, pumps and heat exchangers, to evaluate their design, performance and durability, and
c) approximately 500 hours of experimental powerplant testing to demonstrate powerplant durability and performance.

Task 2 - With the information and test results generated in Task 1, prepare and furnish the preliminary designs, design layouts and drawings of a complete prototype hydrogen-oxygen fuel cell power supply system for manned space vehicle applications to meet the power level, performance, and reliability requirements to be specified by NASA.

# II GENERAL DESCRIPTION OF FUEL CELL POWERPLANT

The fuel cell powerplant consists of three major sections 1) the fuel cell module assembly, 2) the hydrogen circulation loop for heat rejection and exhaust product removal, and 3) the reactant and powerplant controls. This entire powerplant system is presented schematically in Figure 1 and in isometric form in Figure 2.

The fuel cell module consists of an assembly of cells electrically connected in series to provide the desired voltage and of a size sufficient to provide the required power. Each cell consists of a hydrogen electrode with gas access ports, an oxygen electrode with similar gas supply ports, and an electrolyte compartment with the necessary electrical insulating material between electrodes. Oxygen supplied to a cell reacts with water in the electrolyte at reaction sites in porous nickel oxide electrodes, and hydroxyl ions are created. The reaction requires electrons which are provided through the external load from the hydrogen electrode. After formation the hydroxyl ions migrate through the electrolyte to the reaction sites in the porous nickel hydrogen electrode, where they combine in a second reaction to form water and provide electrons to the external circuit. The overall reaction combines hydrogen and oxygen to form water, electricity and excess heat. The module assembly includes any pressure vessel and insulation required for the desired operating conditions. For the low pressure Bacon type fuel cell, the operating conditions are normally a pressure from one to three atmospheres and a temperature of 500°F with concentrated potassium hydroxide (75-90 per cent).

The hydrogen circulation loop provides a means of rejecting excess heat and removing the exhaust product, i.e., water. The loop consists of a hydrogen circulation pump, drive motor, heat exchangers and a water separator. The circulation pump produces an excess of hydrogen which passes behind each hydrogen electrode. The low concentration of water vapor in the incoming gas mixture permits diffusion of water vapor from the porous electrode structure, and the enriched mixture of water vapor and hydrogen is purged from the cell to the heat exchanger. The first exchanger, a regenerator, is included to conserve heat at low power conditions by transferring heat from the outgoing hydrogen-water vapor to the incoming mixture. The second heat exchanger rejects excess heat to an external sink and condenses the water vapor for ease of separation of the hydrogen-water mixture. This is actually accomplished in a centrifugal separator driven on a common shaft with the circulation pump. The recirculated hydrogen, now containing a low water vapor concentration, is pumped back to the fuel cell either through the regenerator or not, as the operating conditions may require.

The reactant controls consist of differential pressure regulators which maintain a constant discharge pressure with respect to a reference pressure regardless of the quantity of flow. The powerplant controls consist of a hydrogen flow control valve to maintain the quantity of recirculated hydrogen, a radiator bypass valve to adjust the water content in the recirculated mixture, a regenerator selector valve to provide for conservation of heat at low power conditions, and a standby heater control to maintain operating temperatures under no load conditions.

Design layouts and analytical studies of this type of fuel cell powerplant have been completed in company-sponsored programs and the data has been available for this contract. Detail drawings, check assemblies and analytical studies have also been completed specifically for this contract.

## III DETAILED DESIGN OF EXPERIMENTAL POWERPLANT

A major effort during the first quarter was the detailed design of the 250 watt experimental fuel cell powerplant using state-of-the-art concepts. The approach philosophy was to include design features which would ultimately be compatible with requirements of powerplants for manned space applications. The immediate object was the design and operation of a completely self-sustaining ground operated powerplant to prove the feasibility of the system. For ease of testing, the first powerplants will include a water-cooled condenser instead of a space radiator system.

The powerplant provides a nominal 250 watts at 12 volts DC and includes controls for reactants flow, voltage, and heat and water removal, over a range of power requirements. All internal parts of the fuel cell module and the controls have been designed to space flight standards of weight and reliability. However, no attempt has been made to lighten or hermetically seal external housings. To facilitate testing, the controls are in separate functional units rather than packaged as one unit.

Alternate configurations have been designed where they would be of maximum benefit to development of the prototype powerplant. For example, the module has provisions for alternate seal arrangements, and alternate controls using different concepts for regulating electrolyte concentration have been provided.

### A. System Selection

The factors used in selection of the powerplant configuration and operating conditions, with a discussion of alternate configurations in each of the three major sections of the powerplant, are presented below.

a. Fuel Cell Module

The selected cell nominal operating conditions are:

1) 500°F cell temperature,
2) 20 psia reactant pressure,
3) Electrolyte with 85 per cent KOH by weight, and
4) Module performance 12 ± 1 volts, net output of at least 250 watts.

Cell Temperature - For good cell performance and for minimum radiator size, the operating temperature should be as high as practicable. The 500°F operating temperature is the maximum temperature consistent with the cell seal design. Figure 3 shows the change in the output of a module as the cell temperature is varied. The effect of temperature on output is critical at high current densities. Because minimum weight of a module is dependent on attaining high current densities, it is vital to operate at temperature levels as high as practical.

High cell temperatures are also required in order to reduce radiator size and weight to a minimum. This reduction is due not only to the increased radiator inlet temperature but also to the increased water vapor in the cell exhaust. The resulting high condensing temperature is an additional factor minimizing radiator size.

Cell Pressure - Studies of the influence of operating pressure have shown that the near optimum cell pressure level for a space engine will be about 60 psia. Higher pressure levels will result in higher module case and radiator weight. To facilitate testing, a reactant pressure of approximately 20 psia (15 psia electrolyte pressure) was chosen for the initial experimental engines. With only minor modifications to the housing and controls, these engines will operate at 60 psia. Figure 4 shows the effect of cell operating pressure on radiator size for a typical flight powerplant.

Electrolyte Concentration - Once the cell temperature and operating gas pressure are established, the equilibrium water concentration in the electrolyte is fixed by the hydrogen recirculation ratio (pounds of hydrogen circulated/pounds of hydrogen consumed). This in turn is established by the level required for water removal and the allowable heat loss from the module. A recirculation ratio of at least 7 is required for water removal. Studies of the module heat balance demonstrated that of the total heat to be removed: 1) a minimum of 250 Btu/hr could be expected by natural convection and radiation from the module surface and by conduction through electrical leads and supports, and 2) the remaining heat must be removed by the recirculating hydrogen. For these reasons a recirculation ratio of about 8 was selected. The resulting electrolyte concentration is 85 per cent potassium hydroxide.

Module Performance - Figure 5 shows individual cell voltage versus current density for the best and poorest performance anticipated. Also shown between these limits is the performance for a single cell during a 1000-hour endurance test. Superimposed on the individual cell performance curves are total power output curves for a 15 cell assembly, indicating the various current densities required to provide 280 or 310 watts. (These totals include 250 watts net with either 30 or 60 watts of powerplant parasite load.) With the intermediate performance achieved in the endurance test, the current density is 153 amperes per square foot for a 30 watt parasite load and the module terminal voltage is 13 volts (15 x .87). With higher parasite loads the current density increases and the terminal voltage decreases corresponding to 190 amps/ft$^2$ and 12 volts respectively for a 60 watt parasite load. These current densities will provide long electrode life and are typical of the current densities required for minimum system weight.

If the extreme conditions should develop, either high parasite loads and the poorest performance or low parasite loads and the best performance, the number of cells can be changed to 16 and 14 cells respectively to conform with terminal voltage limitations. This approach also narrows the range of current densities indicated at the extremes with 15 cells.

b. Reactant Feed Section

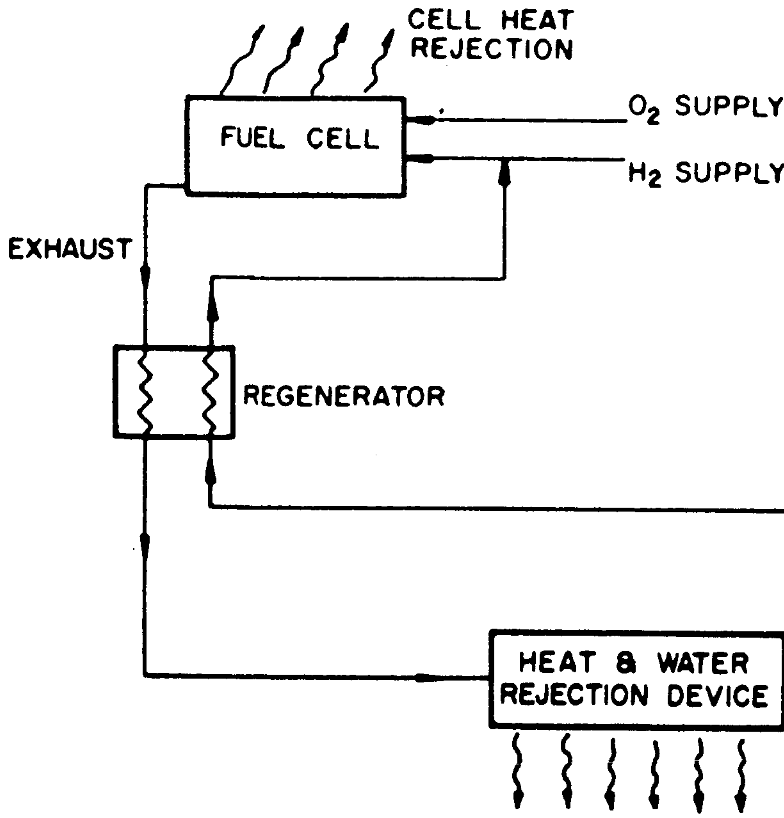
It is required that the feed section provide reactants to the fuel cell at a constant pressure regardless of flow rate. At the cell inlet, the reactants must be gaseous but the temperature will depend on the type of storage system considered. While development of a reactant feed system is beyond the scope of this program except for pressure regulators, analytical studies are available which have considered the problems to be expected in a space application. The results of these studies will be available for inclusion under Task II of the present contract. For the current fuel cell feasibility program, reactants will be supplied from high pressure gas cylinders at room temperature.

c. Heat and Water Removal Section

The functions of this portion of the powerplant are twofold. Potable water must be removed from the cell discharge gases and the waste heat from the fuel cell section must be rejected to space.

Two criteria must be observed in the design of the section. The powerplant heat balance must be properly adjusted to keep the modules at a fixed operating temperature over the power range. The other criterion is that hydrogen must be circulated through the fuel cell to remove the water vapor formed in the reaction.

These two criteria combine to present a requirement for a powerplant cycle shown in simplified schematic form below.




The water formed at the hydrogen electrode must be removed to prevent a reduction in electrolyte concentration. A logical method of removing the water is to circulate excess hydrogen over the hydrogen electrode to remove the water vapor where it is formed. The effectiveness of the hydrogen circulation in removing the water formed is dependent on the circulation rate, the amount of water vapor in the hydrogen flow or essentially condenser exit temperature, as well as the cell operating pressure, and temperature. Analytical estimates of the expected electrolyte concentration as a function of circulation rate are shown in Figure 6 for the experimental powerplant design conditions and two condenser temperatures. Also shown is an estimate of the ratio of water removed from the cell to the hydrogen circulated. These estimates assume that the partial pressure of the water vapor at the cell exit was equal to the partial pressure of the water vapor for the electrolyte at that temperature and concentration. The data points shown on the curve, actual test points discussed in a later section, apparently confirm the analytical approach being assumed.

A second equally important function of the recirculating hydrogen is to transfer the waste heat from the fuel cell. The recirculation flows required for these two functions are not necessarily the same. At low power conditions heat removal considerations require lower flows than water removal while at high power the converse is true. A regenerator is provided to heat the recirculating flow at the low powers before it enters the fuel cell. The source of heat in the regenerator is the hot exhaust gas leaving the fuel cell. The proper amount of regeneration is provided by a regenerator bypass valve which determines the amount of recirculating hydrogen flow that passes through the regenerator. At high power operation all the flow will bypass the regenerator, increasing the cooling capabilities of the recirculation hydrogen flow.

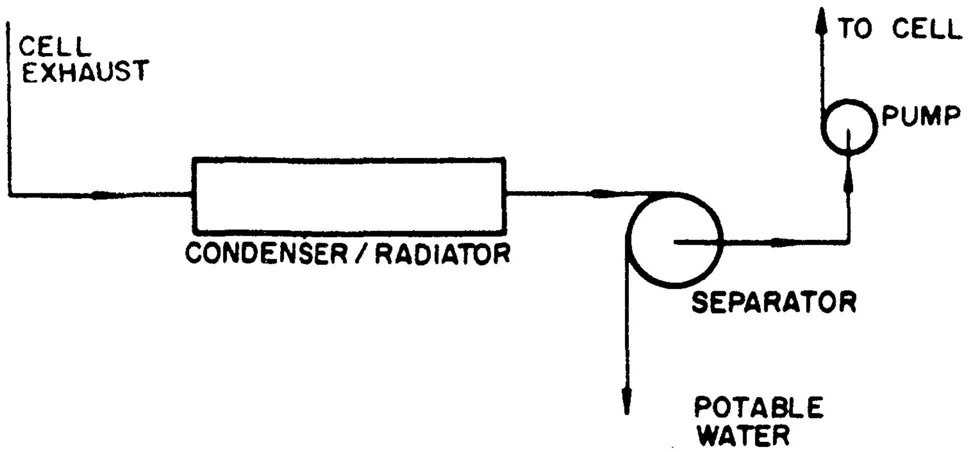
Devices to reject heat and water are numerous. However, for a manned space application it is desirable to recover the potable water generated by the fuel cell. Because of the quantity of water involved, the choice is limited to systems utilizing a condenser. Since the system will have to operate in a zero gravity environment, a separator is also required to remove the condensate from the circulating hydrogen stream.

Some of the more feasible water and heat removal concepts for space systems are listed below. Each of the concepts incorporates a mechanical separator to remove the liquid water from gases.

1) Condenser-radiator (selected for this project)
2) Gas-gas separator/condenser-radiator
3) Diffusion separator/condenser-radiator

<u>Condenser - Radiator</u> - A sketch of the radiator/liquid-gas separator design is shown below.

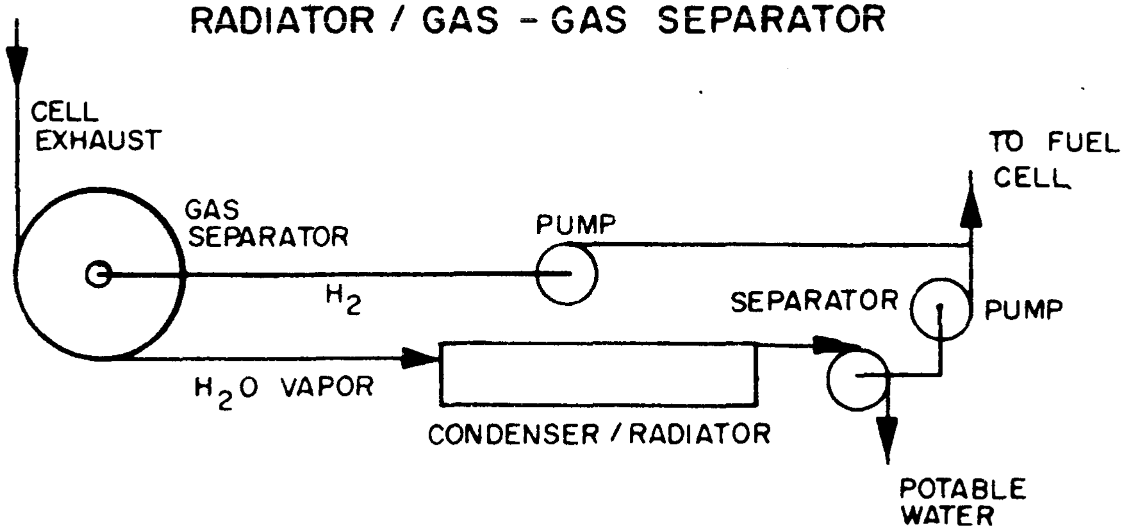
Cell exhaust gases are circulated through a potable water condenser/radiator where the gases are cooled. Some of the water vapor is condensed and the liquid water is separated from the water vapor and hydrogen gas in the centrifugal separator. Potable water is available from the separator and the mixture of water vapor and hydrogen gas is pumped back to the fuel cell. The low pumping and separator powers and the relative simplicity are the primary advantages of this system.




## RADIATOR/GAS-LIQUID SEPARATOR

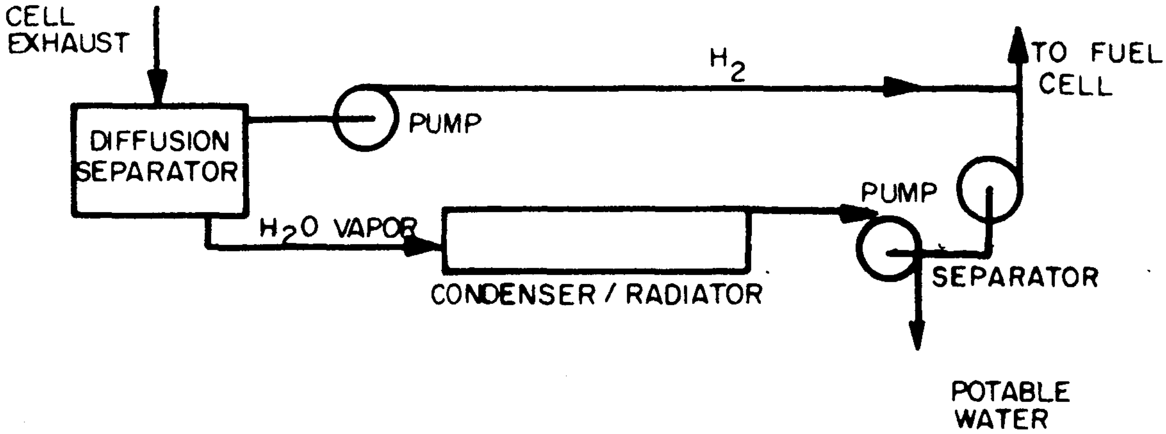
<u>Gas-Gas Separator/Condenser-Radiator</u> - An alternate design partially separates the fuel cell exhaust mixture of water vapor and hydrogen gas in a centrifugal separator. This design is shown schematically below.

## RADIATOR / GAS - GAS SEPARATOR




In this design some of the hydrogen gas is removed from the cell exhaust by a centrifugal separator to increase the specific humidity of the vapors flowing to the condenser and thus reduce the size of the radiator. Systems'optimization studies have shown this design to be approximately 24 per cent heavier than the design described previously. The heavy weight is due primarily to the weight penalty associated with state-of-art gas-gas separator designs. This design is also more complicated than the first design in that an additional pump and separator are required.

Diffusion Separator/Condenser-Radiator - The third design incorporates a porous material to partially separate the cell exhaust mixture by differential diffusion. This is shown schematically below.




RADIATOR / DIFFUSION SEPARATOR

In this design some of the free hydrogen in the cell exhaust is separated from the water vapor. This is accomplished in a set of porous paladium tubes through which only hydrogen may pass. The amount of hydrogen separated is determined by optimization studies which balance two factors, the condenser weight decrease with higher mixture quality and the system weight increase with higher hydrogen pumping powers.

Systems optimization studies have shown this design to be about the same weight as that using a condenser-radiator. The radiator area is also about 10 per cent smaller than the first system; however, because of the added complexity associated with the additional pump, the first system discussed is preferred.

B. Thermodynamic Description

Values of flow parameters, temperatures and pressures are summarized in the following table for the nominal 250 watt rating.

## Estimated Experimental Fuel Cell Powerplant Design Data

| | |
|---|---|
| Net Power | 250 watts |
| Voltage | 12 volts |
| Current density | 150-190 $amps/ft^2$ |
| Number of cells | 15 |

### FUEL CELL

**INLET**

Reactants

| | |
|---|---|
| Temp. | 60°F |
| Pressure | 20 psia |
| $O_2$ | 0.2264 lb/hr |
| $H_2$ | 0.0283 lb/hr |

Recirculating Flow

| | |
|---|---|
| Temp. | 170°F |
| Pressure | 20 psia |
| $H_2$ | 0.204 |
| $H_2O$ | 0.063 |

**EXIT**

| | |
|---|---|
| Temp. | 500°F |
| $H_2$ | 0.204 |
| $H_2O$ | 0.318 |

Module heat loss by radiation and convection 250 Btu/hr

### CONDENSER

$H_2$ Inlet

| | |
|---|---|
| Temp. | 500°F |
| Pressure | 19.9 psia |
| $H_2O$ | .318 lb/hr |
| $H_2$ | .204 lb/hr |

$H_2$ Exit

| | |
|---|---|
| Temp. | 80°F |
| Pressure | 19.7 psia |
| $H_2$ | 0.204 lb/hr |
| $H_2O$ vap. | 0.063 lb/hr |
| $H_2O$ liq. | 0.255 lb/hr |

Heat rejection 624 BTU/hr

### PUMP-SEPARATOR

| | |
|---|---|
| Power | 25 watts |
| $\Delta T$ | 90°F |
| $\Delta P$ | 0.3 psia |

C. Mechanical Design

a. Fuel Cell Module

The fuel cell module is the major component of the powerplant. It consists of an assembly of fifteen cell units connected in series to provide the nominal 12 volts potential. The cells selected for use in this module are of the latest type evolved from the original Bacon design. For both static testing and projected flight, the module is oriented so that the cell stack is in a vertical position; i.e., the cell surfaces lie in a horizontal plane. In the experimental unit this is done to give the flexibility of being able to run without seals if so desired. It would be done in the flight system to minimize the effects of g loading on the hydrostatic head of the potassium hydroxide.

A unit cell consists of hydrogen and oxygen electrode assemblies separated by the KOH electrolyte and electrically insulated from each other by teflon O-ring seals (Ref. Figure 7). Each electrode assembly consists of a dual porosity sinter, a gas manifold, and a seal housing. The assembly is designed to withstand both normal operating pressure differentials and flight g loads. This is accomplished by providing a series of dimples on the manifold back up plate. These are brazed to the electrode to provide the required reinforced sandwich type structure. The hydrogen manifold is also provided with baffles to control the circulation path of the fuel. The hydrogen is metered to each gas manifold by an orifice in the manifold inlet tube. Inlet and discharge tubes to the manifolds are 0.094 inch diameter nickel tubing. For short term testing manifold tubes are connected to main feed lines by Teflon jumpers, and for long term evaluation by a brazed ceramic coupling. Electric heaters for module warmup are placed between the cell units. The fifteen cells are held by 12 tierods of AMS 6304 which also serve to place the teflon seal in compression. The compressive load of the tierods is distributed through two end plates which are electrically insulated from the module assembly. Due to the creep characteristics of Teflon, it was felt that long term testing might reveal the necessity of providing housing followup on the seals. In the selected design the tierods may be spring loaded to maintain a compressive load over the expected creep range. In an alternate design, (Ref. Figure 8) machined Teflon rings backed with wave washers replace the O-rings. To complete the module options, an alternate pressure jacket has been selected to accomodate reference pressures greater than 15 psia.

The insulated jackets provided for the module are fabricated from stainless steel sheet 0.031 inch thick. They enclose a thick layer of Thermobestos insulation. For operation at elevated pressures, an Inconel pressure vessel is placed within the insulation. The Thermobestos was selected because it is readily available in standard shapes although higher performance materials such as Min K or Si-44 would be used for space application.

b. Heat Exchangers

One of the two heat exchangers used in this system is a simple counterflow coil consisting of two concentric tubes with a 2 to 1 diameter ratio. This coil is used as the regenerator and is placed within the insulation in the module jacket. Placing the regenerator in this location helps to reduce the heat rejection from the system by eliminating radiation losses from an otherwise separate housing. The selected diameter ratio with the outside tube diameter set at 1.0 inch gives the required heat transfer with an acceptable level of pressure loss.

The other heat exchanger is the condenser which replaces the radiation device used in space application. This is a single coiled tube through which the mixture of hydrogen and water vapor passes. The coiled tube is enclosed in a jacket through which the coolant flows. For test purposes, the temperature may be held constant to simulate a radiator. However, since the control system is able to automatically compensate for variations in cooling temperature, the coolant temperature can be allowed to vary to evaluate control reactions.

c. Pumps and Separation System

For simplicity the pump and separator are both mounted on the same shaft. The separator follows current jet engine de-oiler technology and the pump is a single stage, shrouded impeller centrifugal type. A number of alternates in separator configuration and in types of bearings have been provided. The pump design speed is 20,000 rpm and the initial testing is being done with filled Teflon bearings. Future testing will evaluate both carbon and antifriction bearings. No attempt has been made to incorporate water drinking facilities or large capacity storage in this experimental system.

d. Control System

The reactant pressure regulation system consists of the hydrogen, oxygen and reference pressure regulators. These maintain a preset differential between gas (fuel or oxidant) and reference pressures. Since the reference pressure is equal to the electrolyte pressure, these regulators control the pressure drop across the electrode.

To minimize change in regulated pressure with change in flow rate, the overall spring rate of the system was made low. This, coupled with a large diaphragm area, produces a large valve travel for small pressure variations. The expected control characteristic of this unit is regulation within ± .25 psi over a flow range from one-tenth to twice normal flow. To insure against system overpressure, each control contains a relief valve actuated by the same lever-diaphragm combination which moves the supply valve.

The reference pressure regulator maintains a pressure of 16 ± 0.5 psia on the electrolyte through connecting inert gas passages between the hydrogen and oxygen regulators and the fuel cell module. The primary causes of system pressure variation to which this control must respond are gas expansion due to initial system warmup and to functional system leakage. The nitrogen flows that are anticipated for this regulator are so low that it has been designed on the theory that it may never be necessary to lift the valve from its seat but merely to occasionally relieve the load to the point that it becomes an imperfect seal. Spring adjustments and alternate valves are provided to make this regulator more versatile.

e. Hydrogen Flow Control

In performing its required functions of temperature regulation and water removal, the hydrogen-water vapor mixture must pass through the regenerator bypass valve, the condenser bypass valve and flow control which sets the hydrogen flow rate through the fuel cell module.

In both the regenerator bypass valve and the flow control, the valve settings are determined by the bellows movement, which, in turn, are motivated by temperature sensing bulbs located in the fuel cell module. The bellows assemblies consist of the temperature sense fluid-filled bellows and evacuated reference pressure bellows. The temperature bulb and bellows are filled with a critical temperature phase change fluid, para-cymene, which gives the desired strong actuation sense in the required temperature range. Springs and valve seats are adjustable for calibration over the pressure signal range which can be extended by substituting new springs.

The condenser bypass valve functions to maintain a constant temperature mixture flow to the water separation system. This is accomplished by sensing mixture temperature with a liquid-filled expansion bellows and using the resulting bellows movement to modulate the condenser bypass valve. The design criteria affecting the design of the bypass are similar to the control components already discussed. As before the expansion fluid selected is para-cymene. This fluid is in extensive use and has been found very satisfactory for similar applications. To allow for possible angular misalignment of the valve which could cause poor sealing, a spherical valve and conical seat combination are used.

f. Override Temperature Control

A module heater system is included in the system for starting warmup and to maintain a minimum acceptable temperature level at low power output conditions. The heaters are fabricated from nichrome wire woven into Fiberglas mats. These are installed between individual cells in the module. Again module temperature is sensed by a para-cymene-filled bulb and bellows combination. An external loading spring is incorporated in this control to set the system pressure equal to the vapor pressure of the para-cymene at the desired switching temperature. An ambient pressure reference bellows is employed to eliminate any ambient pressure control bias. Manual switching is used to provide warmup energy from an outside source.

A list of check assemblies indicating design details completed specifically for this program is tabulated below:

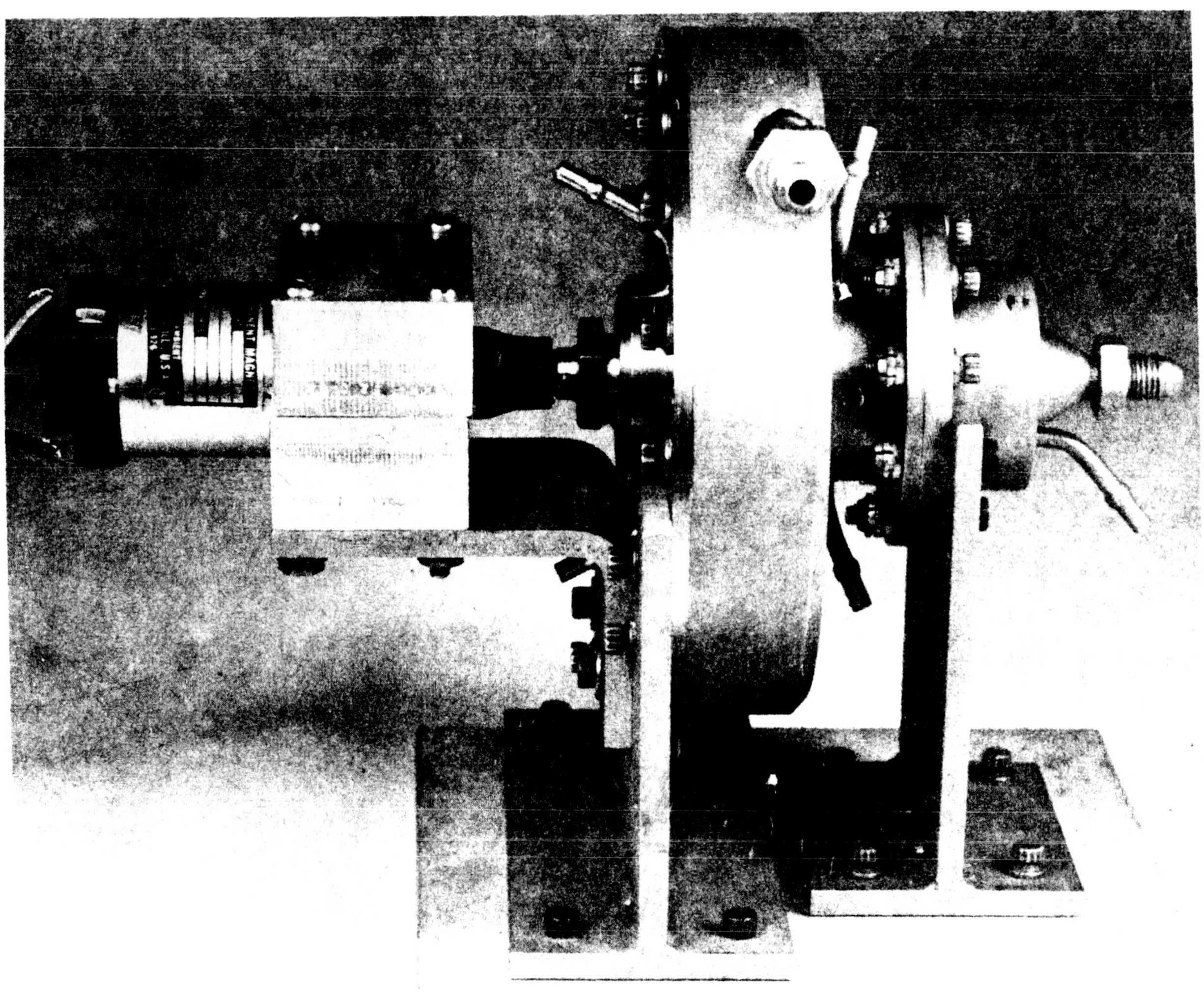
Assembly Drawings

| Title | Number |
| --- | --- |
| Regenerator and Module Jacket | L-50249 |
| Regenerator and Pressurized Module Jacket | L-50678 |
| $H_2$ and $H_2O$ Separator and Circulation Pump | L-50901 |
| Flow Control Valve | L-50902 |
| Regenerator Bypass Valve | L-50902 |
| Reference Pressure Regulator | L-50903 |
| Reactant Pressure Regulator | L-50904 |
| Fuel Cell Module | L-50905 |
| Condenser | L-50906 |
| Condenser Bypass Valve | L-50907 |
| Flow Control Override Valve | L-50908 |
| Heater Control Switch | L-50909 |
| Electrolyte Concentration Control | L-50910 |
| Volume Compensating Bellows | L-50911 |
| Modified Valves and Liners, Reactant Pressure Regulators | L-50912 |
| Modified Flow Control and Regenerator Bypass Valve | L-50913 |
| Electrolyte Expansion Diaphragm | L-50914 |
| Electrolyte Level Control | L-50915 |
| Fuel Cell Assembly | L-50916 |

# IV FABRICATION

The major components for the experimental powerplant have been released to the shop for fabrication. The experimental hydrogen circulation pump and water separator described in the previous section has been completed and is available for test. Fabrication of other components will be completed during the next report period.

The experimental pump and separator were machined from electronic "A" nickel or AMS 5665 bar stock. In some cases, subassemblies were built up by brazing with a gold-nickel braze before final machining operations. Bearings were machined from Teflon, AMS 3651, and reamed through at assembly. No special manufacturing techniques were required or employed.



HYDROGEN CIRCULATION PUMP FOR EXPERIMENTAL POWERPLANT.

# V TEST RESULTS

## A. Experimental Powerplant

Experimental hardware is in the process of fabrication. Initial testing will begin during the period covered by the second quarterly report.

## B. "Breadboard" Powerplant

While components of the experimental powerplant were not available for test during this report period, tests of "breadboard" components (available hardware of an earlier design) were conducted to provide systems experience and to identify early in the program the problems that will be encountered. Tests were conducted on single cells, multicell assemblies, reactant pressure regulators and a hydrogen circulation loop.

### 1. Fuel Cell

A typical "breadboard" test configuration for both single cell and multicell assemblies consisted of vertically placing each set of five inch diameter, dual porosity electrodes in an individual tank filled with electrolyte. The tanks were covered to facilitate the maintenance of a constant weight percentage of water in the electrolyte, generally fifteen per cent. The standard electrode spacing was one-half inch. Reactant gases were supplied to the electrodes at approximately 7 psig. The reactant gases were vented to remove gaseous inerts and the water formed in the electrochemical reaction. The tests were generally conducted with an electrolyte temperature of between 480°F and 500°F at atmospheric pressure. A tubular palladium reference electrode operating on hydrogen provided half cell potentials to aid in the evaluation of electrode performance. An assembled set of electrodes and an electrolyte tank are shown in Figure 9.

#### a. Single Cell Tests

1) Tests were conducted to investigate the effect of temperature on performance at different electrolyte water concentrations. Listed below are the output voltages obtained at a current density of 150 amperes per square foot for various temperatures at an electrolyte water concentration of 15 per cent:

| Volts | Temperature |
|---|---|
| .870 | 500°F |
| .850 | 475°F |
| .825 | 450°F |
| .770 | 425°F |
| .715 | 400°F |
| .645 | 375°F |

The results also showed that the performance decreased as the electrolyte water concentration was increased above 15 per cent. Forty-six and one-half hours of running time were accumulated during these tests. Complete performance curves are shown in Figure 10.

2) The operating design point of present electrode structures is 150 amps/ft$^2$ (134 watts/ft$^2$). Larger loads may be placed on the fuel cell for limited periods. A short test (42 hours test time) was conducted to determine the maximum power available from a fuel cell at a variety of temperatures. The results obtained are listed below:

| Maximum Power Density | Temperature |
|---|---|
| 185 watts/ft$^2$ | 500°F |
| 145.5 watts/ft$^2$ | 450°F |
| 96.2 watts/ft$^2$ | 400°F |

It should be noted that prolonged running at these load conditions would adversely affect electrode life.

3) An investigation of horizontally-oriented fuel cell electrodes spaced one-eighth inch has been initiated. The purpose of conducting this test was to demonstrate satisfactory operation of a compact fuel cell design similar to the experimental power-plant design. Although only thirty hours of test time have been accumulated, the initial operation of the cell and the preliminary results obtained indicate that this is a feasible configuration. The electrodes and housings for a two cell assembly are shown in Figure 11.

4) The effect of the hydrogen recirculation rate on water removal for different radiator temperatures was simulated on a single cell to provide additional data for the design of the hydrogen recirculation loop components. The reactant gas was saturated with water before entering the fuel cell and was passed through a condenser after leaving the cell before being vented. The temperature of the saturated hydrogen entering the fuel cell and the temperature of the hydrogen - water gas mixture leaving the condenser were equal, so that the water collected from the condenser was equivalent to the water removed from the fuel cell. The results obtained showed that a recirculation flow rate of 8.6 times the hydrogen consumption rate is required to maintain an electrolyte water concentration of 15 per cent at equilibrium conditions with a radiator temperature of 80°F.

At these conditions, 1.3 pounds of water will be removed from the fuel cell for every pound of hydrogen recirculated. Three hundred and twenty-five hours of running time were accumulated while conducting these tests. A more complete set of the results obtained, along with analytical estimates, are shown in Figure 6. The experimental data closely approximated the analytical estimates and component design work is continuing on this basis.

b. Multi-Cell Tests

1) A 250 watt, 14 cell insulated fuel cell module has been constructed to evaluate multicell operation and for conducting investigations on powerplant control equipment. Eventually the module will be employed in a complete "breadboard" fuel cell powerplant. This module has been operated for 145 hours with an average output of 252 watts at 12.3 volts. It operates in the range of the proposed fuel cell powerplant (250 watts at 12 ± 1 volts) and thus offers a readily available fuel cell module upon which to conduct the initial tests of experimental powerplant accessory equipment. The assembled fuel cell module and the bottom portion of its insulated oven are shown in Figure 12. The control panel for operating and evaluating the performance of this rig is shown in Figure 13.

2) Prior to the assembly of the 250 watt module, a 100 watt six cell module served as its predecessor for conducting multicell tests and investigations are now being carried out concurrently on both assemblies. Four hundred and eighty-four hours of running time have been accumulated on the 6 cell module at an average output of 100 watts at 5 volts. Evaluation of the hydrogen circulation loop and pressure regulator has been conducted on this rig and the tests are discussed in a following section.

3) One of the many company-sponsored activities in the fuel cell field of particular interest to NASA was the operation of a 100 watt, 6 cell display module, Figure 14, demonstrated at Langley Field. The module generated 100 watts at 5.4 volts (0.90 volt per cell) and produced potable water. After the demonstration at NASA the module was restarted upon its return to Pratt & Whitney Aircraft Division by merely reheating the solidified electrolyte and supplying reactant gases to the cells. The assembly was operated for 330 hours under load before the test was terminated.

c. Components

1) Hydrogen Circulation Loop

Preliminary testing of a hydrogen circulation loop has been initiated on the 100 watt, six cell module with the immediate objective of controlling the electrolyte water concentration. The major components of this water removal hydrogen circulation loop were an externally-powered, sliding vane, rotary pump and an air-cooled condenser. The 500°F hydrogen-water gas mixture was pumped from the fuel cell module to the condenser, where a major portion of the water was removed from the system. The 80°F hydrogen-water gas mixture was then returned to the module. The electrolyte water concentration was maintained at a fixed level by regulating the amount of the gas mixture circulated through the condenser, so that only the quantity of water formed in the electrochemical reaction was removed. Dry hydrogen was continually added to this loop to compensate for the hydrogen consumed in the reaction. One hundred and twenty hours of operation have been accumulated on this configuration with no evident ill effects on the performance of the fuel cell module, the longest continuous run being for twenty-two hours. Operation over longer periods of time, however, will undoubtedly require some provision for the removal of gaseous inerts present as impurities in the reactant supply.

2) Reactant Pressure Regulator

The reactant gas pressure regulator shown in Figure 15 has satisfactorily completed over 300 hours of maintenance-free operation on 100 watt, six cell module assemblies. This control relies on a spring-loaded diaphragm to sense the discharge pressure and the flow is regulated by means of a mechanical linkage between the diaphragm and the metering valve to maintain a constant discharge pressure while under a variable demand. While testing of this control was conducted with an inlet pressure of 75 psig, recent bench testing has shown it to be capable of handling the flow requirements of a 250 watt powerplant with inlet pressures as low as 20 psig.

d. Breadboard Powerplant

A complete "breadboard" powerplant is being assembled. It is expected that such a powerplant will be in operation during the period to be covered by the second quarterly report.

## C. Test Time

The table below summarizes the load time accumulated in conducting the above tests:

| Type of Test | Load Time |
|---|---|
| Experimental powerplant and components | 0 |
| Breadboard powerplant | 0 |
| Breadboard single cell tests | 443.5 |
| Breadboard multicell tests | 579.0 |
| Breadboard hydrogen circulation loop | 120.0 |
| Breadboard reactant pressure control | 314.0 |
| Total load time | 1456.5 hours |

# VI. ANTICIPATED PROGRAM

During the next contract period we anticipate the following program:

A. Complete fabrication of all experimental powerplant components,

B. Conduct bench tests of individual components of the experimental powerplant,

C. Conduct tests of a complete breadboard powerplant, and

D. Conduct tests of experimental powerplant components individually and collectively on the breadboard powerplant.

# APPENDIX A

## Figures

# EXPERIMENTAL FUEL CELL POWERPLANT

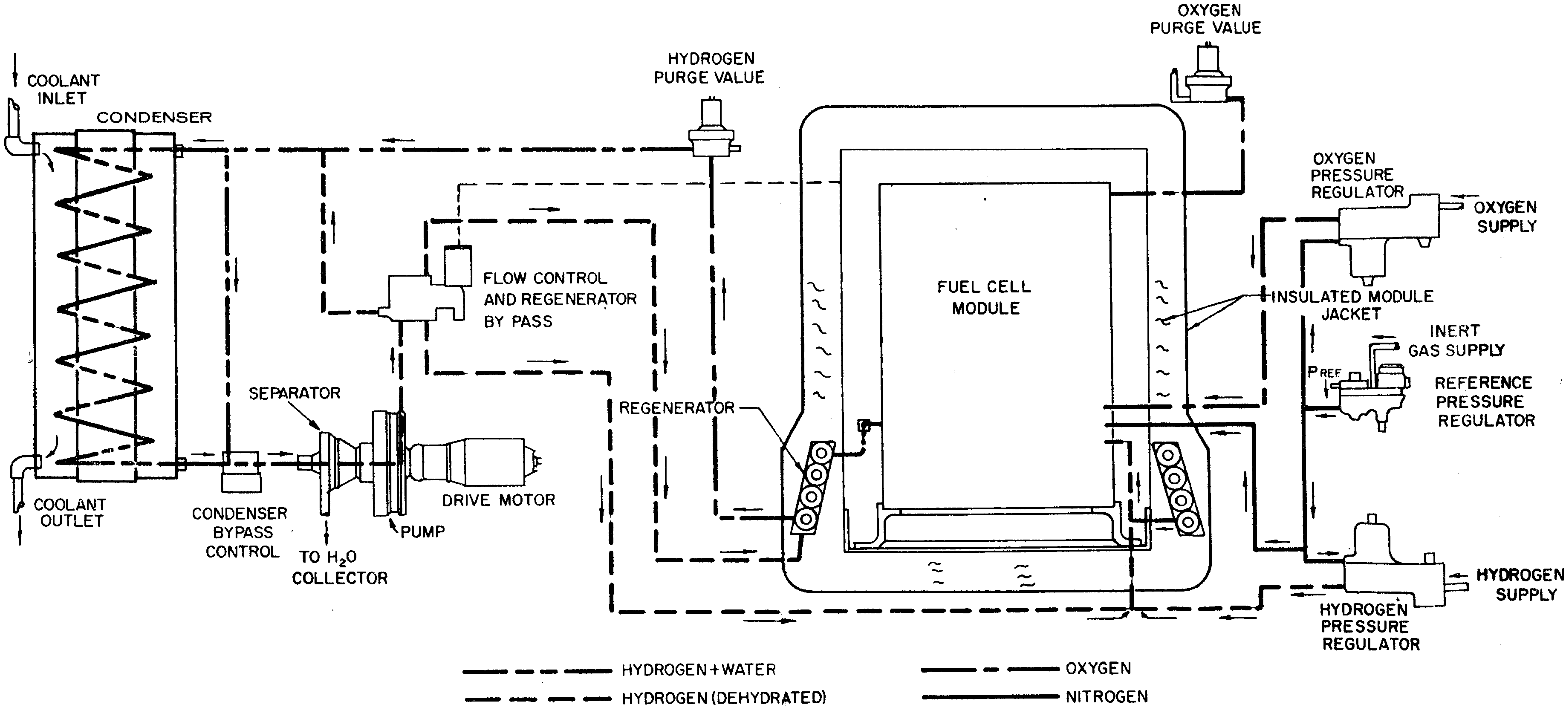



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Figure 1

# EXPERIMENTAL FUEL CELL POWERPLANT

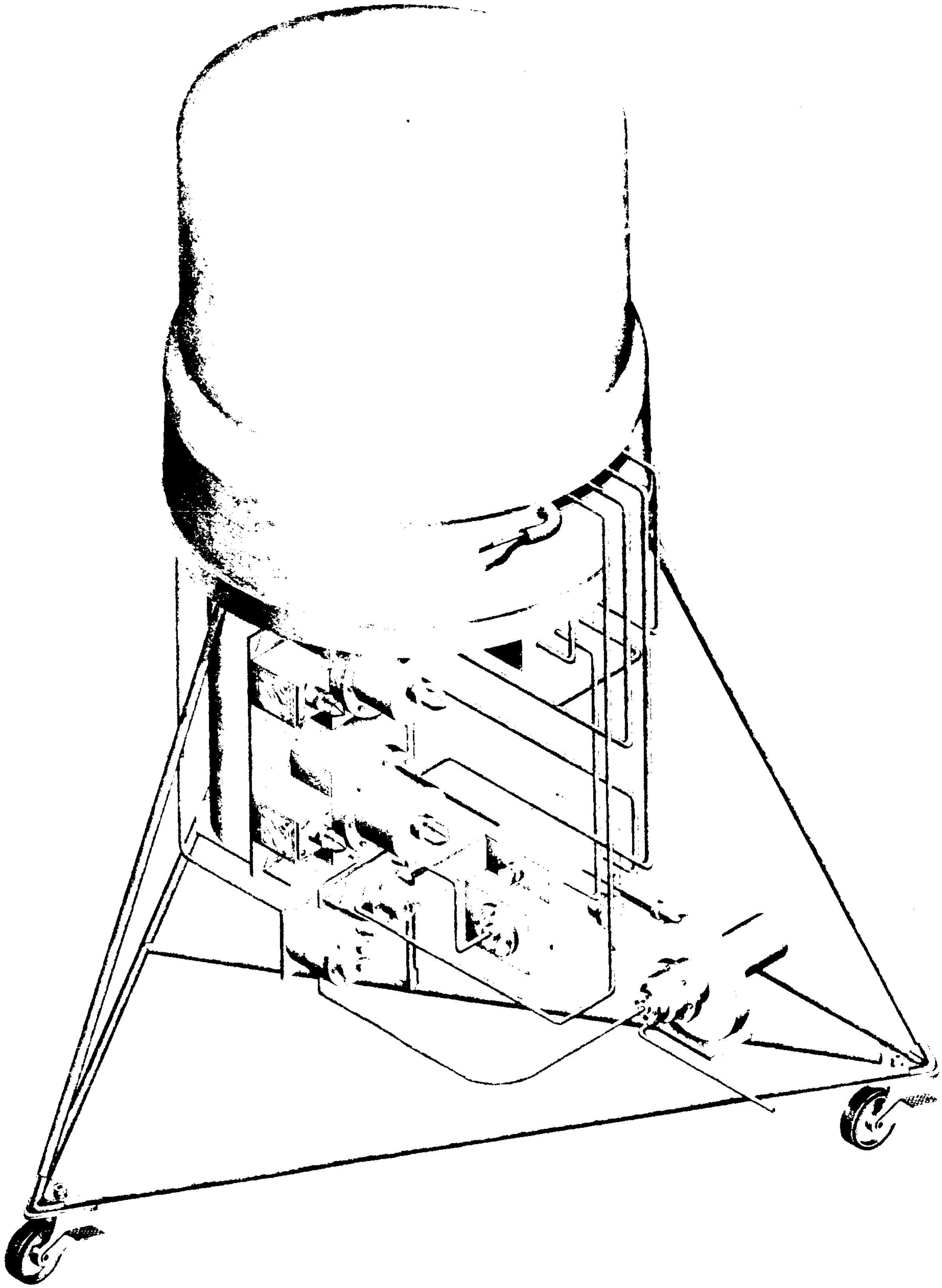

Figure 2

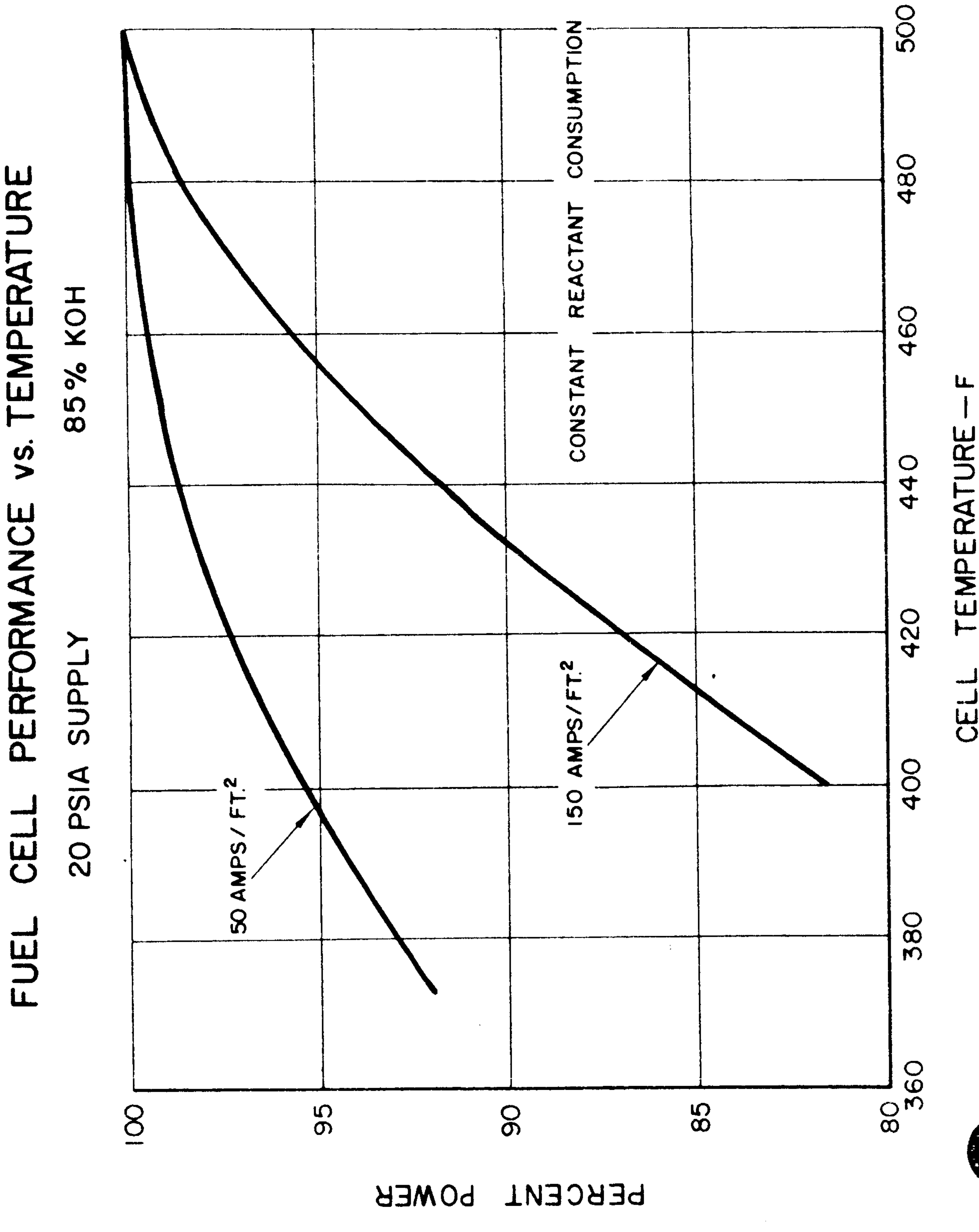


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Figure 3

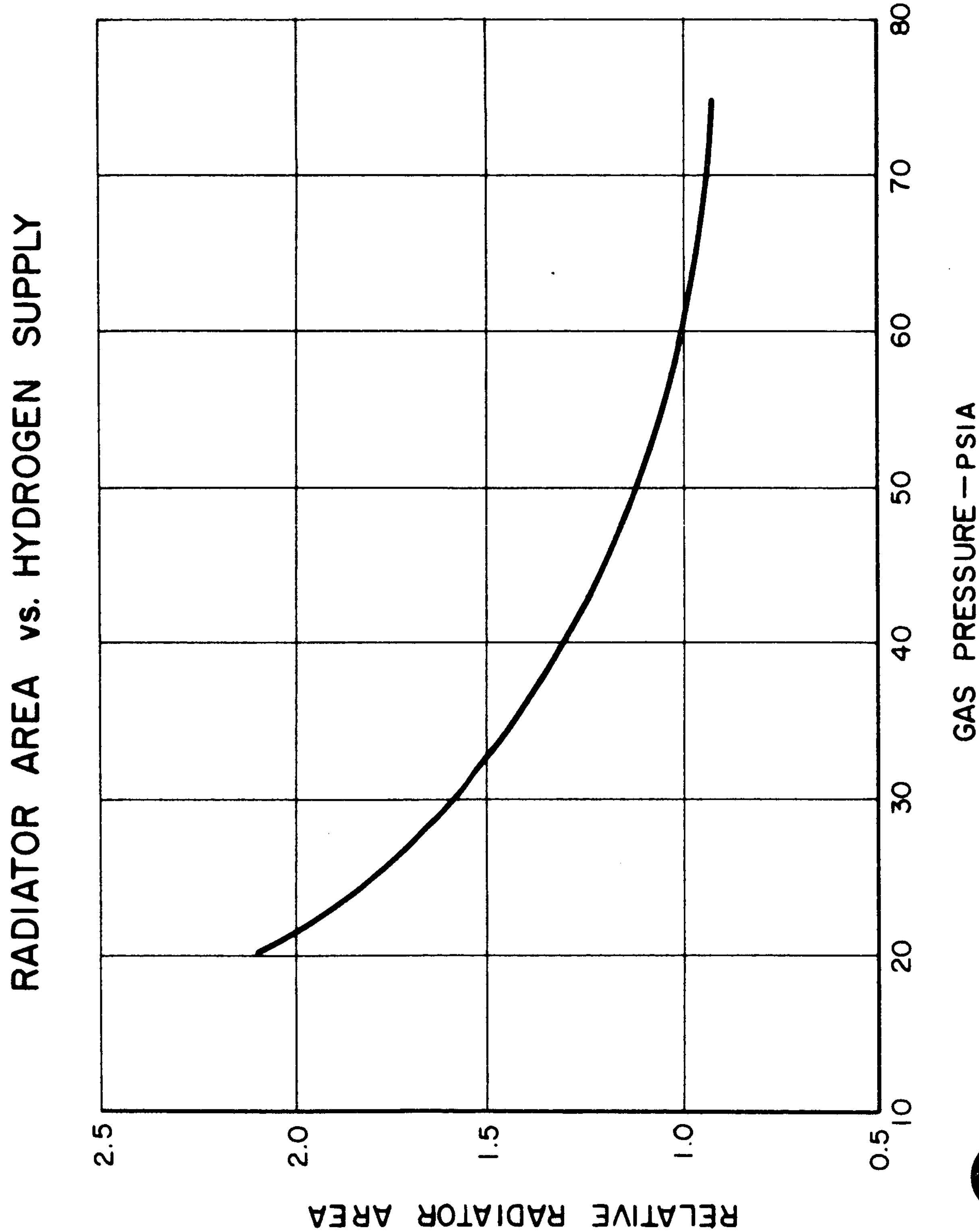


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Figure 4

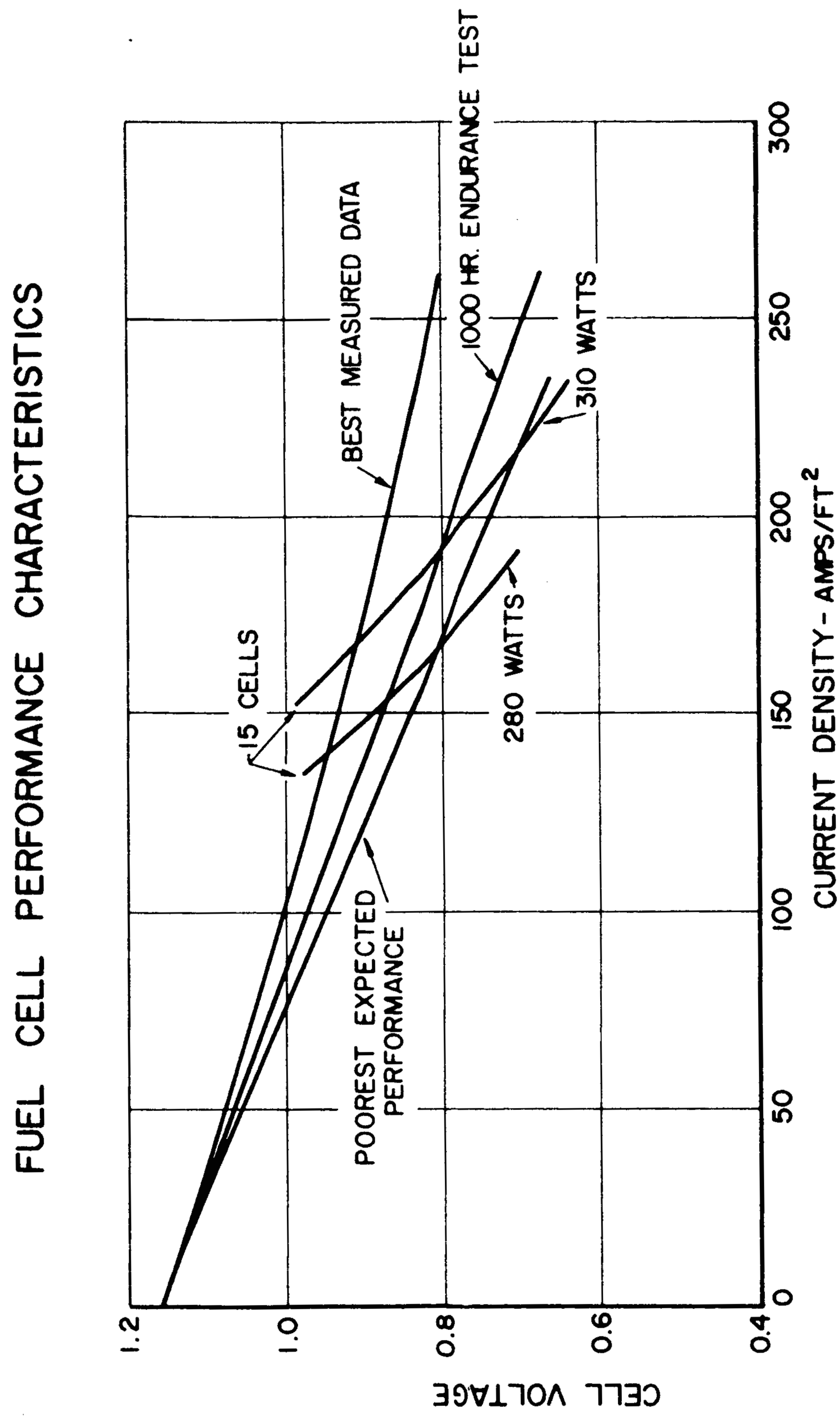


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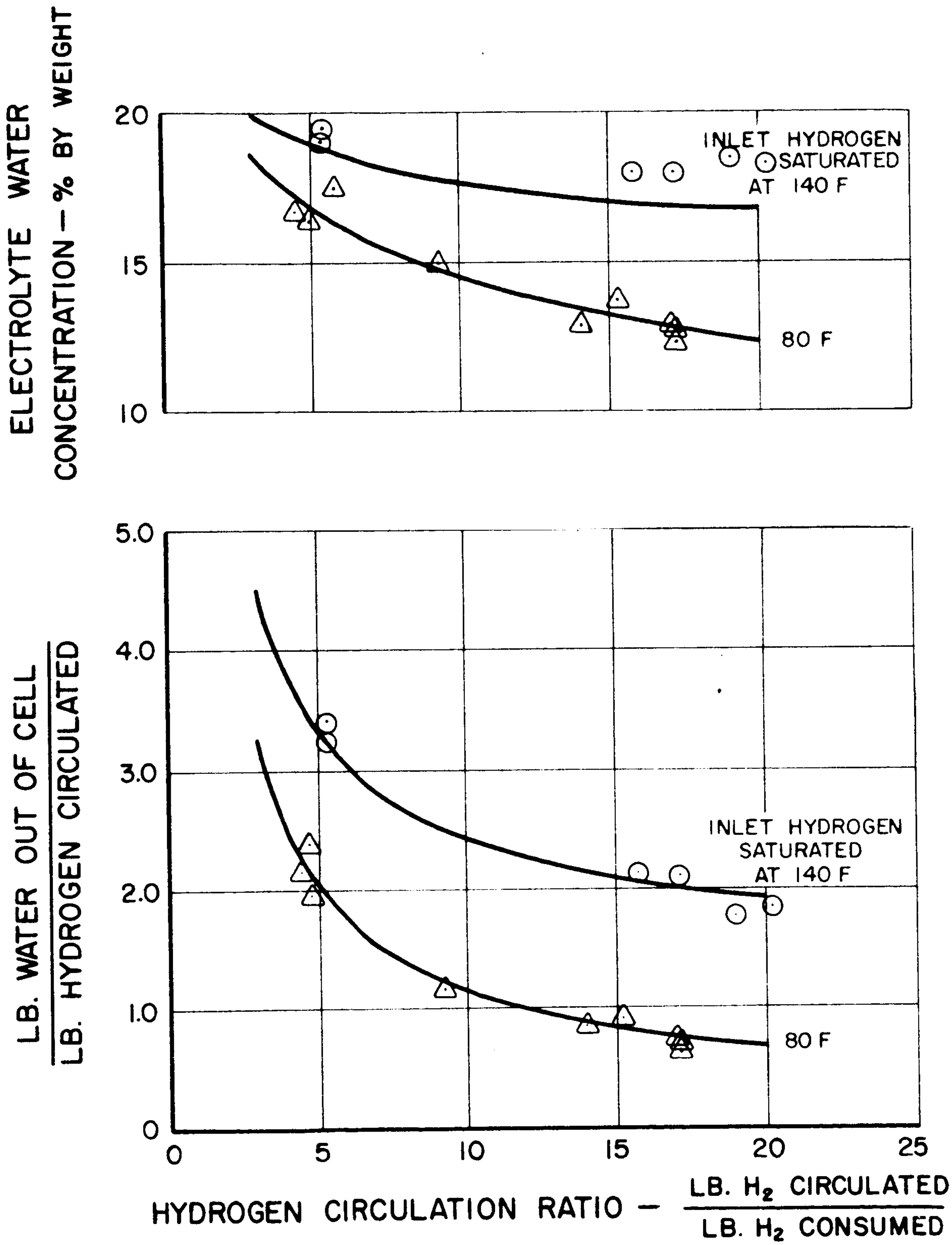
Figure 5

# WATER REMOVAL & ELECTROLYTE CONCENTRATION VS. HYDROGEN CIRCULATION RATIO



# FUEL CELL DETAIL

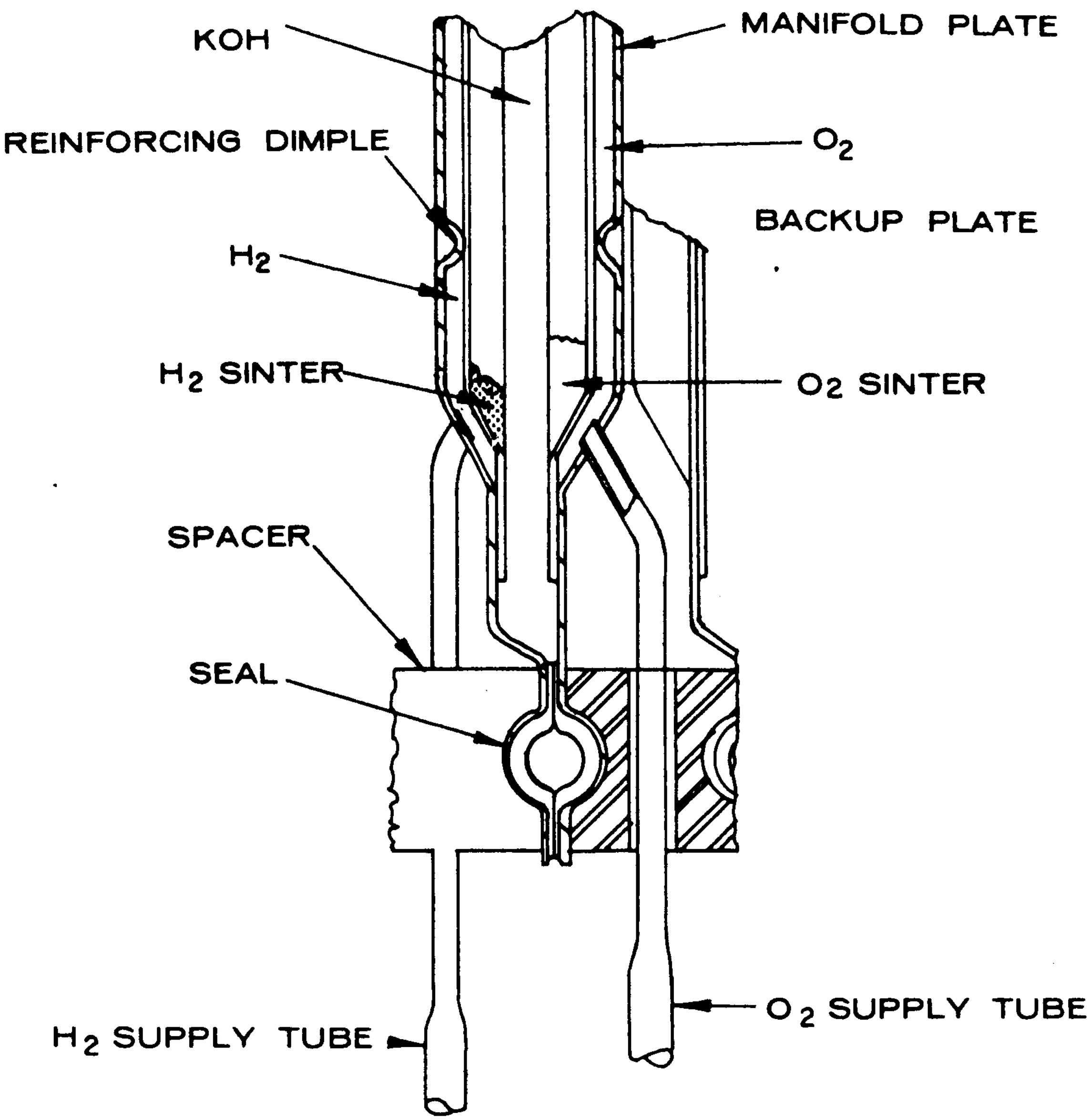



Figure 7

# FUEL CELL DETAIL

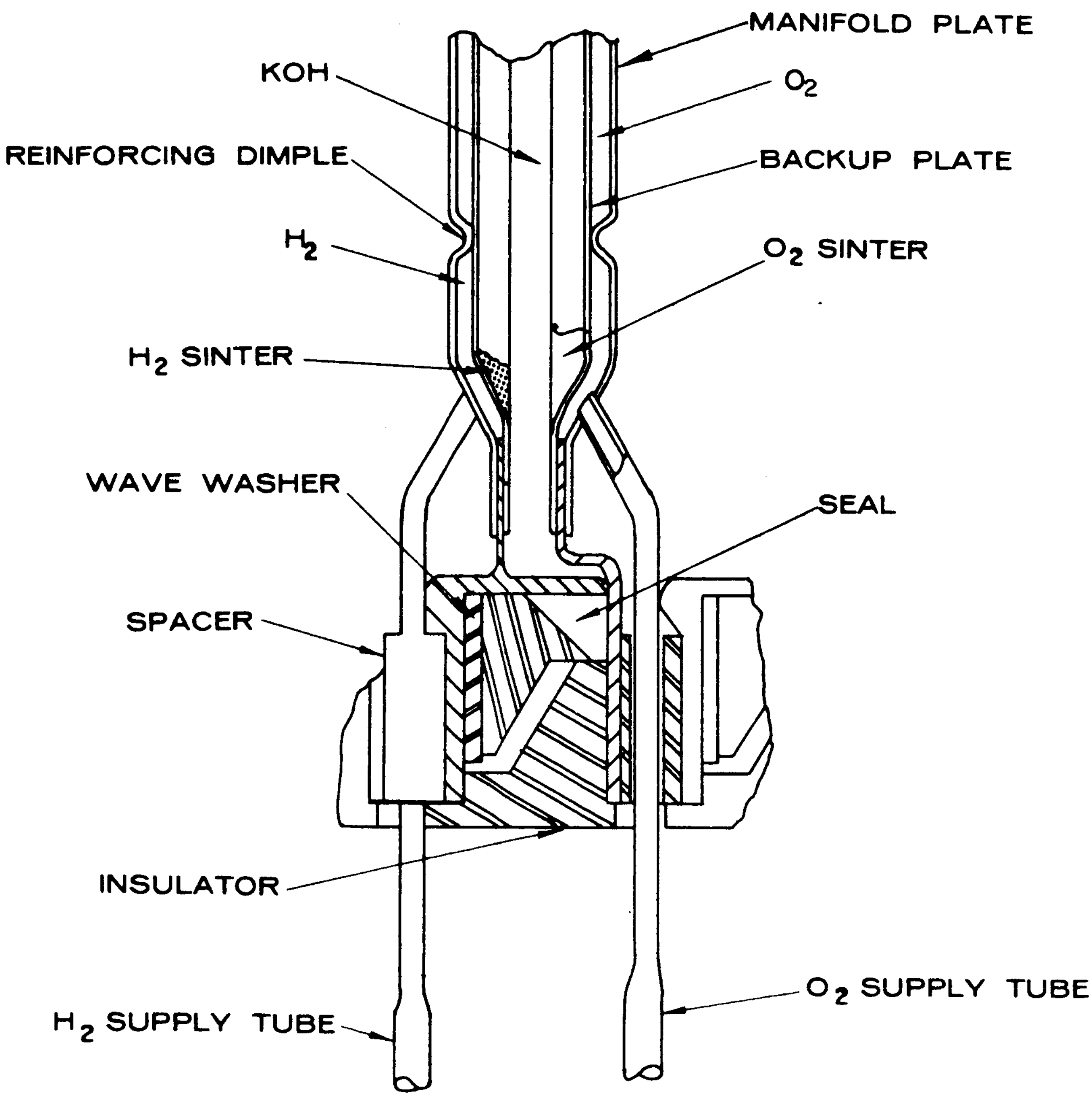
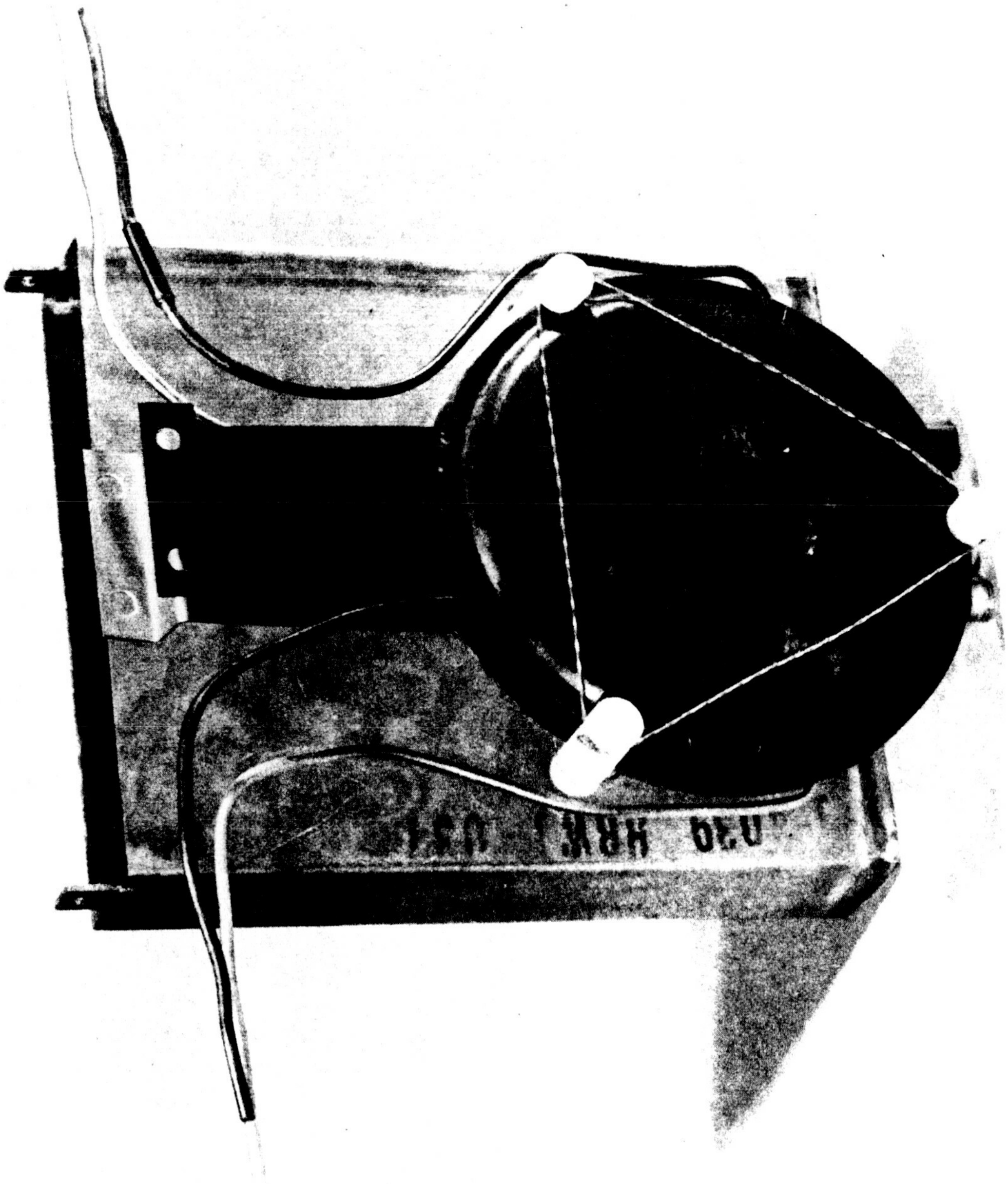



Figure 8



ELECTRODES AND ELECTROLYTE TANK FOR SINGLE CELL OF BREADBOARD POWERPLANT

XP-9252

Figure 9

# EFFECT OF TEMPERATURE ON FUEL CELL PERFORMANCE AT TWO ELECTROLYTE CONCENTRATIONS

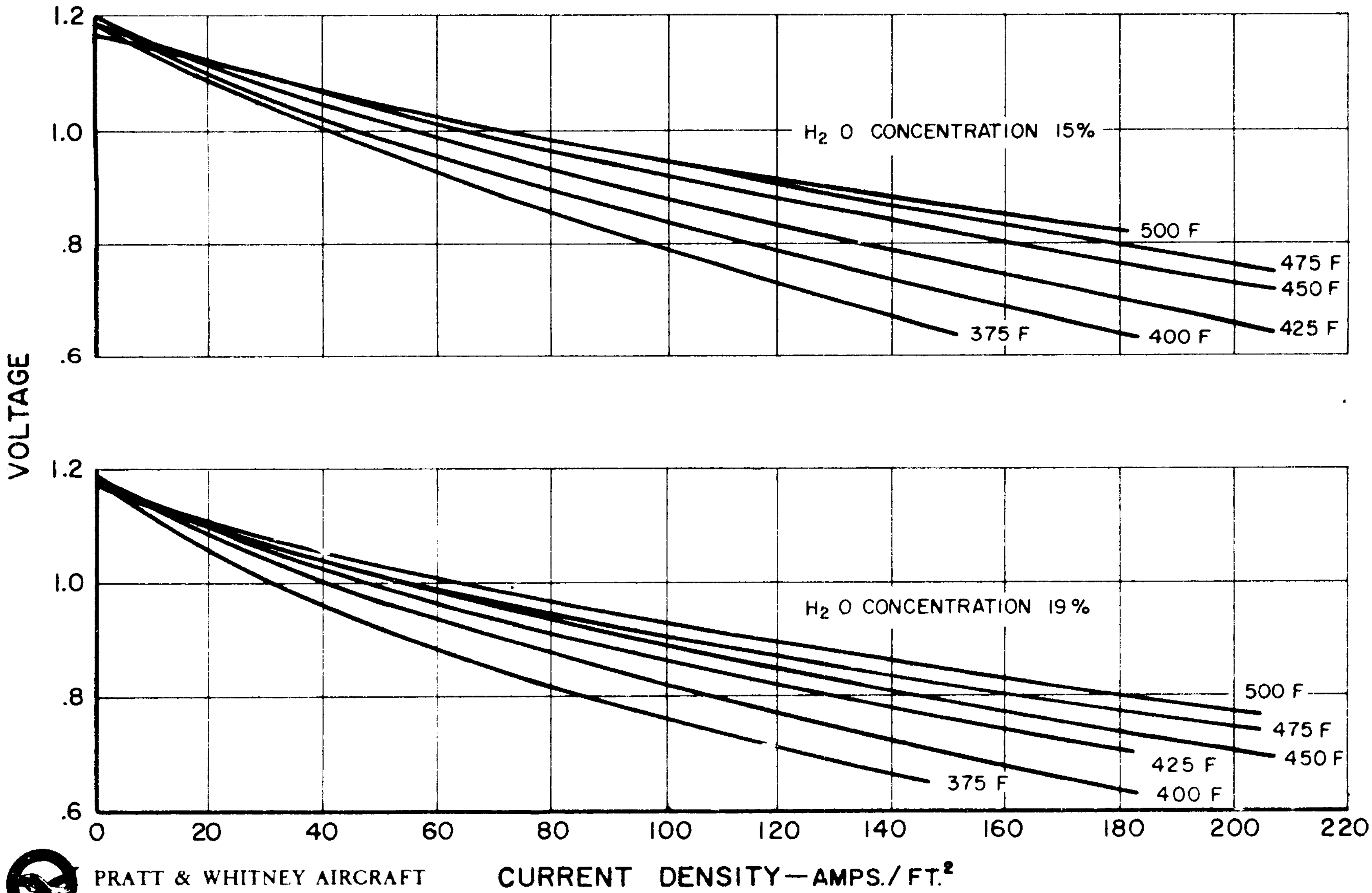



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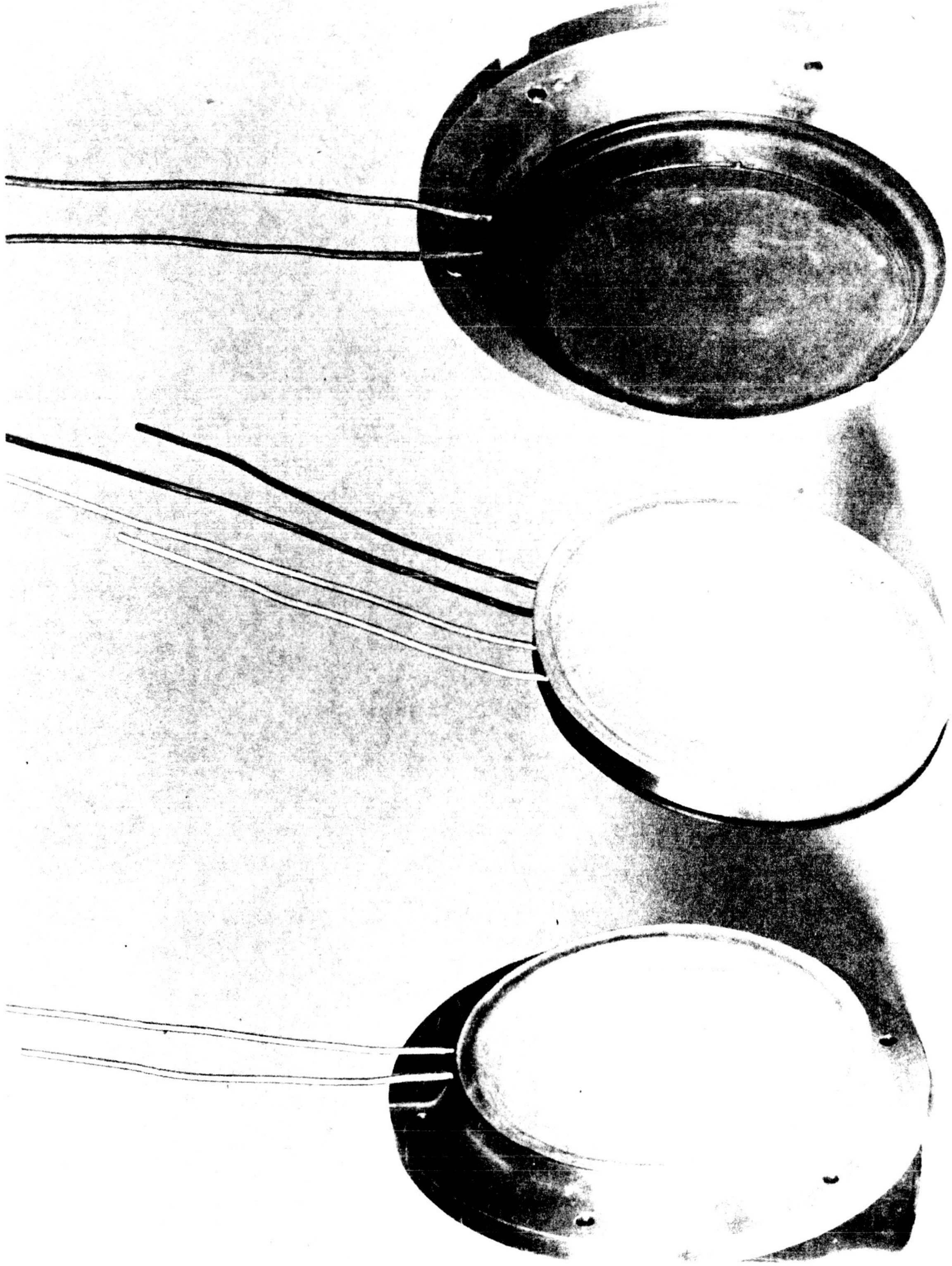
Figure 10

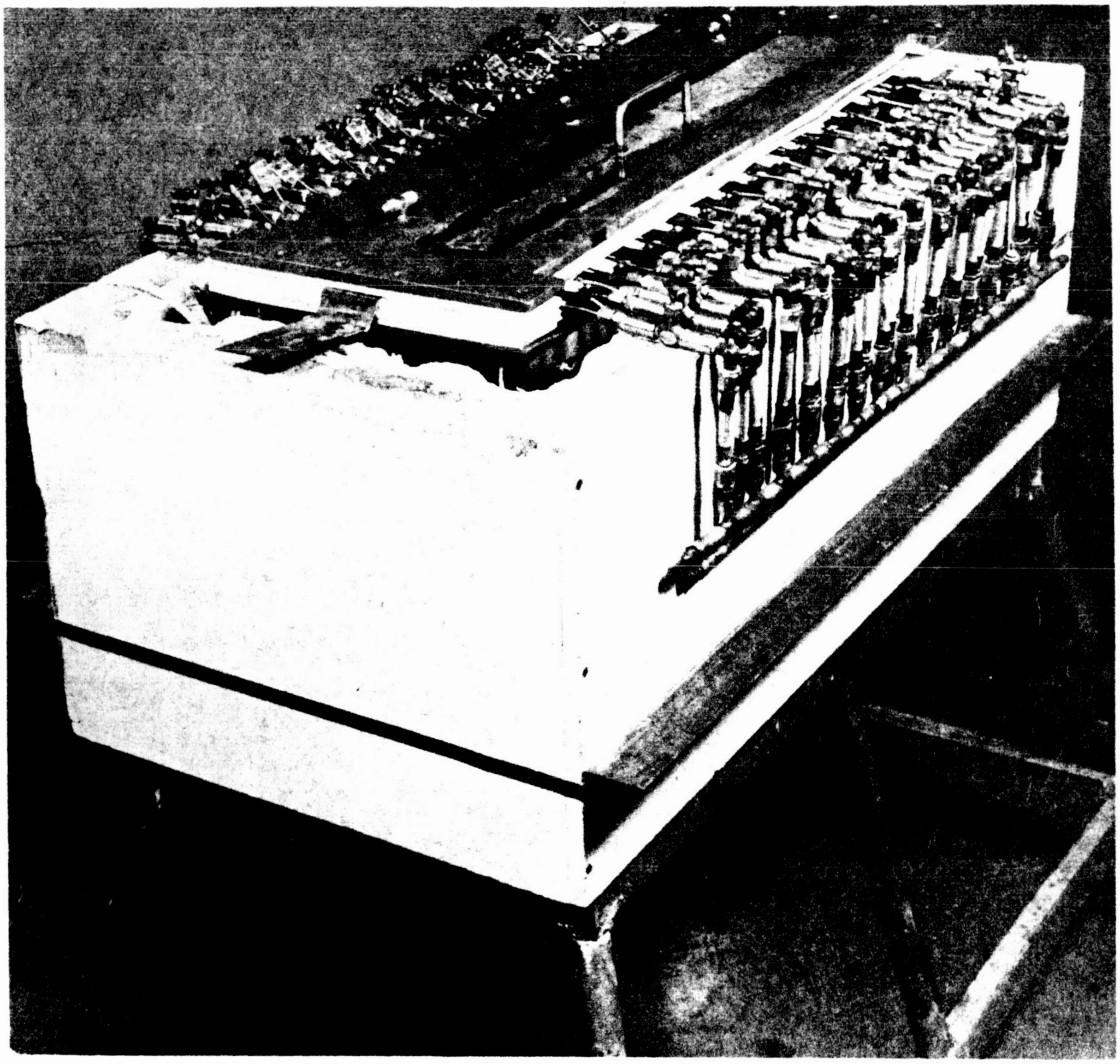


HORIZONTALLY - ORIENTED FUEL CELL ELECTRODES

XP-3849

Figure 11

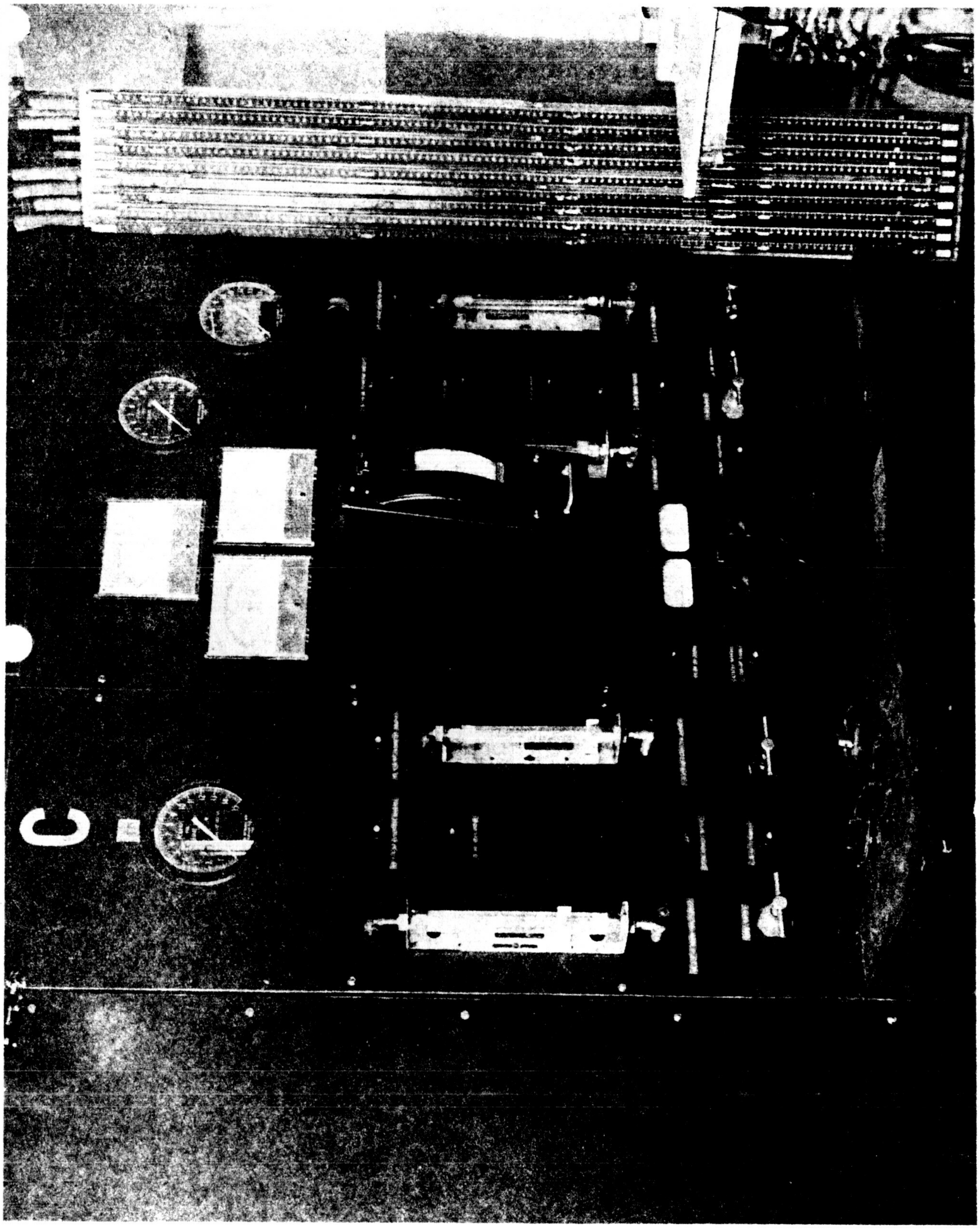
2



BREADBOARD FUEL CELL MODULE

XP-9251

Figure 12



CONTROL PANEL FOR FUEL CELL MODULE TESTS

XP-9248

Figure 13

# LOW PRESSURE FUEL CELL DEMONSTRATION MODEL

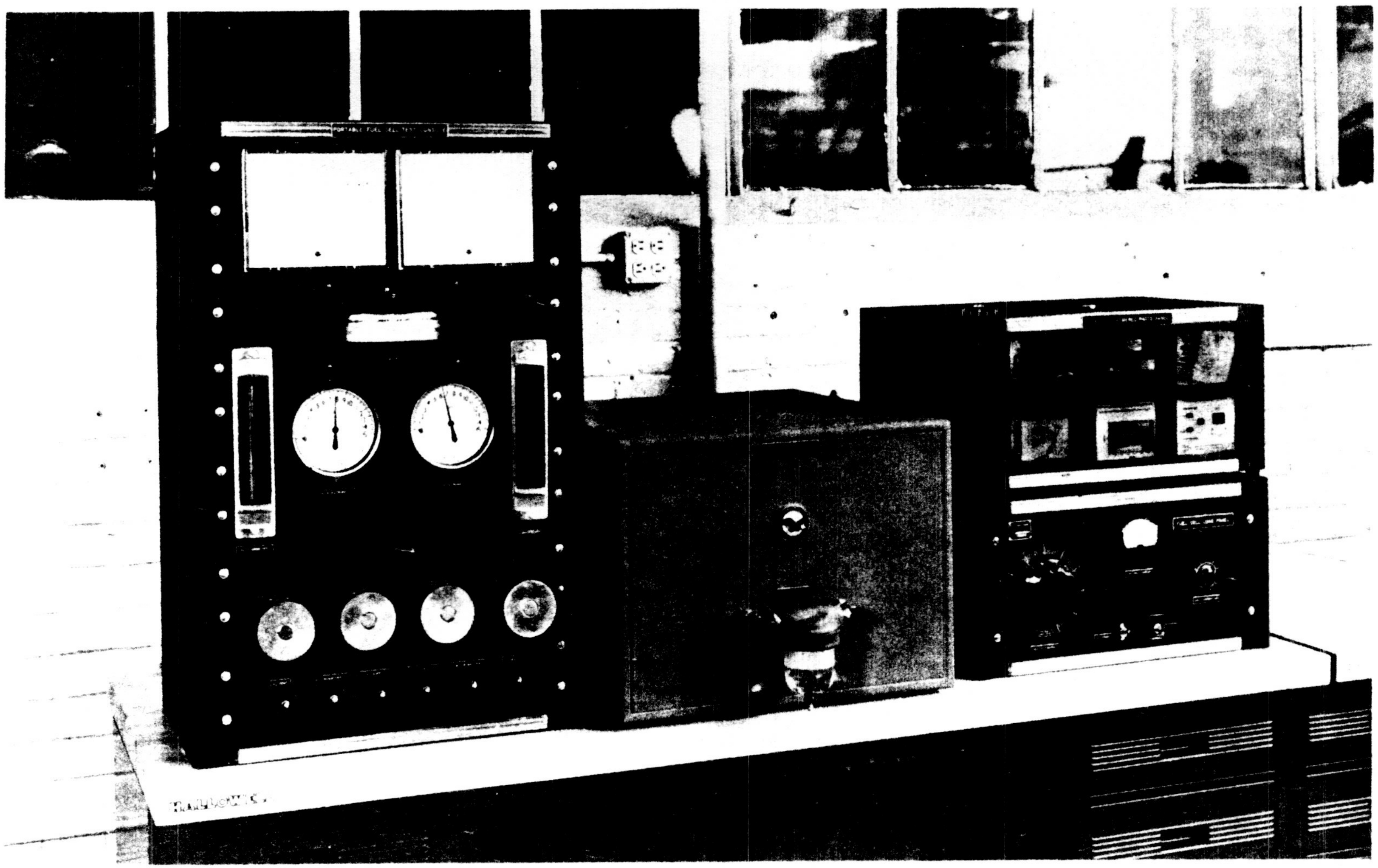


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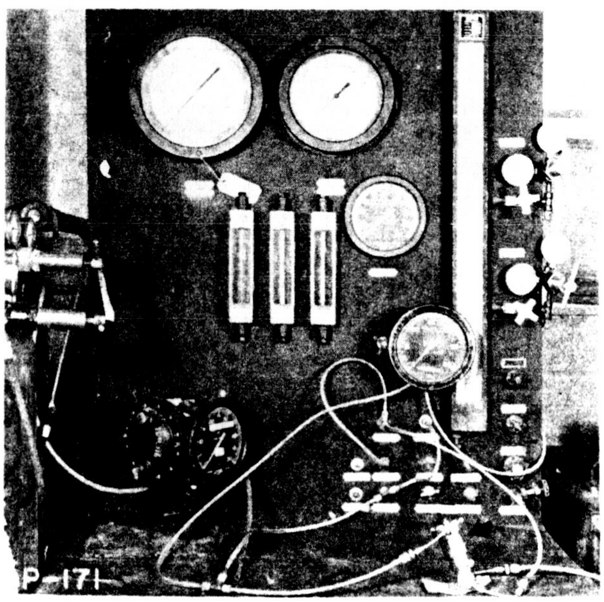
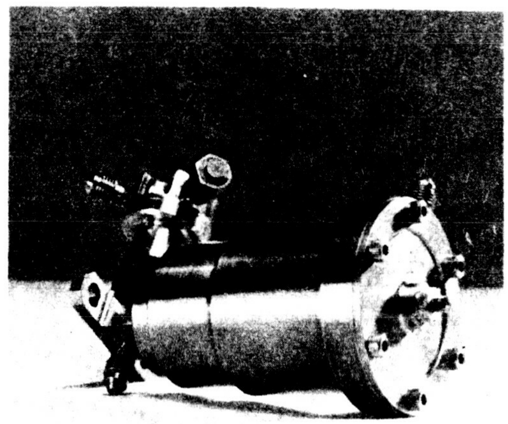
Figure 14

FUEL CELL DIFFERENTIAL PRESSURE REGULATOR




FLOW BENCH



ASSEMBLED PROTOTYPE

Figure 15